

EXPERIMENTAL INVESTIGATION OF POOL BOILING HEAT TRANSFER ENHANCEMENT IN MICROGRAVITY IN THE PRESENCE OF ELECTRIC FIELDS

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INTRODUCTION

In boiling high heat flux levels are possible driven by relatively small temperature differences, which make its use increasingly attractive in aerospace applications, such as compact evaporators in the thermal control of spacecraft environments, heat pipes, and the cooling of electronic equipment. The objective of the research is to develop ways to overcome specific problems associated with boiling in the low gravity environment. One such problem is that in low gravity the critical bubble size for detachment is much larger than under terrestrial conditions, since buoyancy is a less effective means of bubble removal (*Zell (1991), Ervin et al. (1992)*). In terrestrial conditions, bubble detachment is governed by the competition between body forces (e.g. buoyancy) and surface tension forces that act to anchor the bubble along the three phase contact line. In the present study the buoyancy force is substituted by the electric force to enhance bubble removal from the heated surface. Previous studies (*Yabe et al. (1995)*) indicate that in terrestrial applications nucleate boiling heat transfer can be increased by a factor of 50, as compared to values obtained for the same system without electric fields.

The discipline of electrohydrodynamics (EHD) deals with the interactions between electric, flow and temperature fields. The goal of our research is to experimentally explore the mechanisms responsible for EHD heat transfer enhancement in boiling in low gravity conditions, by visualizing the temperature distributions in the vicinity of the heated surface and around the bubble during boiling using real-time holographic interferometry (HI) combined with high-speed cinematography.

METHOD OF STUDY

In the first phase of the project the influence of the electric field on a single bubble is investigated. Pool boiling is simulated by injecting a single bubble through a nozzle into the subcooled liquid or into the thermal boundary layer developed along the flat heater surface. Injection of individual bubbles into the liquid has been used to simulate a physical situation similar to that in subcooled nucleate boiling by *Nordmann (1980), Mayinger and Chen (1986)* and *Ogata and Yabe (1993)*. The advantage of this approach is that the experimenter can control the conditions in the vicinity of the growing bubble. Conversely to the situa-

tion on the heated surface, the conditions in the vicinity of the developing bubble are generally steady. The bubble grows in a uniformly subcooled liquid. Condensation begins immediately, and it takes place over the entire perimeter of the bubble.

Since the exact location of bubble formation is known, the optical equipment can be aligned and focused accurately, which is an essential requirement for precision measurements of bubble shape, size and deformation, as well as the visualization of temperature fields by HI. The size of the bubble and the frequency of bubble departure can be controlled by suitable selection of nozzle diameter and mass flow rate of vapor. In this approach effects due to the presence of the electric field can be separated from effects caused by the temperature gradients in the thermal boundary layer. The influence of the thermal boundary layer can be investigated after activating the heater at a later stage of the research. The described experimental approach offers the advantage of yielding clear and unambiguous results depending on a limited number of controlled process parameters.

EXPERIMENTAL SETUP

Test cell. For the visualization experiments a test cell was developed. The present design incorporates most of the features required for the microgravity experiments, without the special hardware needed to operate it in the aircraft during parabolic flights. The measurement cell is rectangular. All four vertical walls of the test cell are transparent, and they allow transillumination with laser light for visualization experiments by HI. The bottom electrode is a copper cylinder, which is electrically grounded. The copper block is heated with a resistive heater and it is equipped with 6 thermocouples that provide reference temperatures for the measurements with HI. The top electrode is a mesh electrode. Bubbles are injected with a syringe into the test cell through the bottom electrode. Visualization experiments with this test cell are currently underway in the Heat Transfer Laboratory (HTL) of the Johns Hopkins University.

Working fluid. The working fluids presently used in the interferometric visualization experiments, water and PF 5052, satisfy requirements regarding thermophysical, optical and electrical properties.

Instrumentation. A 30kV power supply (Glassman MJ30) equipped with a voltmeter allows to apply the electric field to the electrodes during the experiments. The magnitude of the applied voltage can be adjusted either manually or through the LabVIEW data acquisition and control system connected to a PC. Temperatures of the heated block are recorded using type-T thermocouples, whose output is read by a data acquisition system. Images of the bubbles are recorded with 35mm photographic and 16mm high-speed cameras, scanned and analyzed using various software packages.

VISUALIZED TEMPERATURE FIELDS

HI allows the visualization of temperature fields in the vicinity of bubbles during boiling in the form of fringes. Typical visualized temperature distributions around the air bubbles injected into the thermal boundary layer in PF5052 are shown in Figure 1. The temperature of the heated surface is 35 °C. The temperature difference for a pair of fringes is approximately 0.05 °C. The heat flux applied to the bottom surface is moderate, and the fringe patterns are regular. In the image a bubble penetrating the thermal boundary layer is visible. Because of the axial symmetry of the problem, simplified reconstruction techniques can be applied to recover the temperature field.

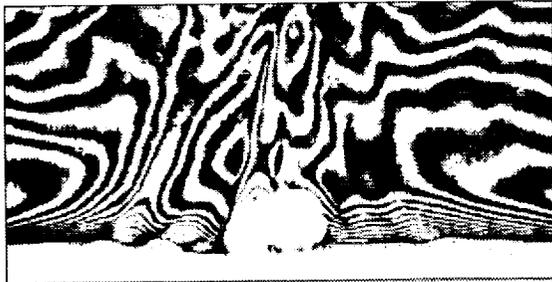


Figure 1. Temperature fields in the liquid phase in the vicinity of the bubble visualized by HI

In Figure 2 the thermal plume developing above the heated surface for more intensive heating is shown. The temperature distribution in the liquid is clearly 3D, and tomographic techniques have to be applied to recover the temperature distribution in such a physical situation. A sequence of interferometric images showing the temperature distribution around the rising bubble, recorded with a high-speed camera is shown in Figure 3. Again, the temperature distribution is 3D, and a more complex approach to evaluation, the tomographic reconstruction has to be taken.

MEASUREMENT OF THE TEMPERATURE DISTRIBUTION

From the fringe pattern temperature distributions that yield important information regarding heat transfer are determined. Two algorithms that allow the quantitative evaluation of interferometric fringe pat-

terns and the reconstruction of temperature fields during boiling have been developed at the HTL of the Johns Hopkins University.

RECONSTRUCTION OF AXIALLY SYMMETRICAL TEMPERATURE DISTRIBUTIONS

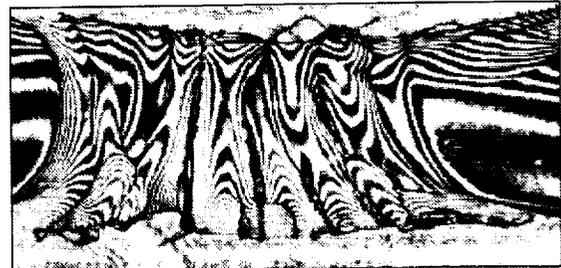


Figure 2. Three-dimensional thermal plume above the heated surface

Data on fringe order and location, obtained by applying digital image processing to the visualization images, serves as input information for the reconstruction algorithm during the first phase of the research, when a single bubble is injected into the working fluid through a nozzle. The bubble is assumed to be axially symmetrical, which significantly reduces the computational effort for quantifying the temperature distribution around the bubble.

In an interferometric image the change of the optical path length of the light beam, caused by the phase difference between object and reference beams, is visualized. In the equation of ideal interferometry the phase change is expressed as the multiple S of the wavelength of light λ ,

$$S\lambda = \int_0^L (n - n_{\infty}) dz. \quad (1)$$

In Eq. (1) n is the refractive index of the measurement state, n_{∞} the refractive index of the fluid during the reference exposure, S the fringe order and L is the length of the path of the light beam through the phase object. This equation is used to reconstruct the temperature distribution in the fluid when the refractive index is constant along the path of the light beam, and the temperature distribution is 2D. To be able to apply the equation of ideal interferometry, apart from these two assumptions, it is necessary to avoid the deflection of the light beam in the thermal boundary layer.

In a boiling liquid a thermal boundary layer is formed around the vapor bubble. The schematic of the physical situation and the path of the light beam in the vicinity of the bubble are illustrated in Figure 4. For the thermal boundary layer around the bubble the requirements for ideal interferometry are not satisfied, i.e. the refractive index is not constant along the path

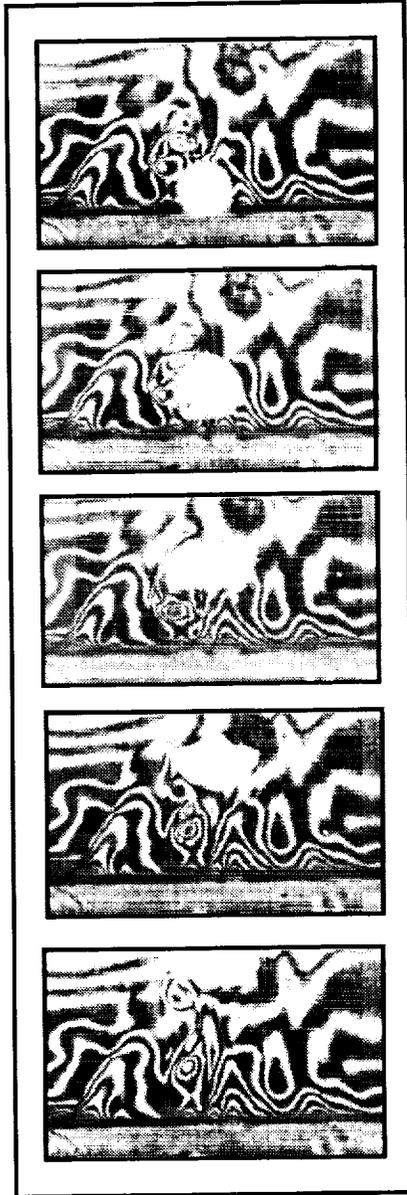


Figure 3. Sequence of 5 interferometric images showing rising bubbles injected into the thermal boundary layer through a nozzle

of the light beam in the working fluid. The refractive index n is a function of the radius r , and the integration limits are also radius dependent. For this physical situation Eq. (1) is modified as

$$S(y)\lambda = \int_{-z_0}^{+z_0} (n(r) - n_\infty) dz \quad (2)$$

In order to recover the temperature distribution $T(r)$ in the thermal boundary layer from the interference fringe pattern $S(y)$, it is necessary to integrate Equation (2) for the physical situation illustrated in Figure 4. For three dimensional refractive index fields this solution can be obtained only when images are

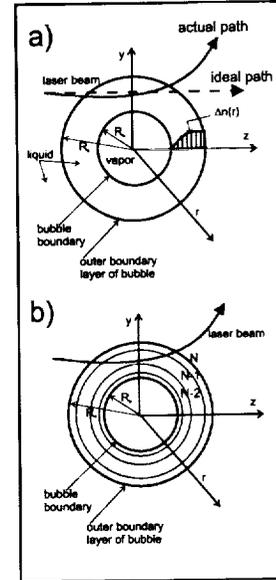


Figure 4. a) Schematic of the deflection of the light beam in the thermal boundary layer formed around a bubble and b) concentric shells introduced to approximate the refractive index variation

recorded for multiple directions of illumination. In the evaluation of temperature distributions in the vicinity of bubbles during boiling, axial symmetry of the refractive index field in the thermal boundary layer is often assumed to simplify the reconstruction process.

For this purpose the thermal boundary layer around the bubble is divided into equidistant concentric shells, and the refractive index is assumed to be constant in each of the shells. For this situation Eq. (2) can be rewritten as

$$S(y)\lambda = S_i\lambda = 2 \sum_{k=i}^{N-1} \Delta n_k \left[(r_{k+1}^2 - r_i^2)^{\frac{1}{2}} - (r_k^2 - r_i^2)^{\frac{1}{2}} \right] \quad (3)$$

An analytical solution of Eq. (3) was described by Abel (Hauf and Grigull, 1970), and the result of the inversion is

$$n(r) - n_\infty = -\frac{\lambda}{\pi} \int_r^{R_b} \frac{dS(y)/dy}{\sqrt{y^2 - r^2}} dy \quad (4)$$

Eq. (4) relates the measured fringe order $S(y)$, a function of the spatial coordinate y , to the change of the refractive index $n(r) - n_\infty$, which has to be determined in the evaluation procedure. For this purpose it is convenient to express the measured fringe order $S(y)$ in the form of a polynomial.

The foregoing evaluation procedure does not account for the deflection of the light beam in the thermal boundary layer around the vapor bubble. Since large temperature gradients are expected in that region, the deflection of the light beam cannot be ne-

glected in boiling experiments. In order to incorporate the deflection into the evaluation procedure, a temperature profile $T(r)$ is initially assumed. This allows to determine the path of the light beam as well as the determination of the optical path length and the phase shift $S(y)$ in the thermal boundary layer. In addition, the exit angle of the light beam is known, which allows to account for the deflections and phase shifts outside the boundary layer (in the bulk fluid and in the windows of the test cell). A computer code has been developed at the HTL that allows to vary the assumed temperature profile $T(r)$ and the boundary layer thickness δ in an iterative procedure, until the calculated values of the fringe order match the measured ones $S(y)$.

OPTICAL TOMOGRAPHY

Tomographic techniques were initially developed for medical applications, and nowadays they are becoming increasingly available in engineering measurements (Mewes, Herman, Renz, 1994). Medical applications are steady, as opposed to engineering problems where the "patient", the temperature field, typically cannot be maintained steady for extended periods of time. This is especially true for boiling with typical bubble frequencies up to 1 kHz. Thus tomographic reconstruction techniques developed for medical applications are not suitable for the study of high-speed, unsteady heat transfer processes.

In tomography, the measurement volume is sliced into 2D planes. In the present study these planes are parallel to the heated surface. The objective is to determine the values of the field parameter of interest in these 2D planes. The field parameter is the change of the refractive index of the liquid in the measurement volume caused by temperature changes. By superimposing data for many 2D planes recorded at the same time instant, the 3D temperature distribution in the measurement volume is recovered.

Mathematical Model. The schematic in Figure 5 illustrates the basic principles of measuring the field function f in one of the 2D planes. The 2D plane is generally irradiated from multiple directions, two of which are indicated in Figure 5. A ray i irradiating the measurement volume can be uniquely described by the angle θ_i and its distance ρ_i from the origin. The directions of irradiation of the two rays shown in Figure 5 are described with the angles θ_m and θ_n . As ray i passes through the measurement volume, changes of physical properties, such as temperature of the fluid in the measurement volume, change the physical properties of the ray. These changes are then measured in form of a projection value Φ_i . In the present study this corresponds to the change of the refractive index, which causes a phase shift between the reference and

measurement beams of the setup for HI. The phase

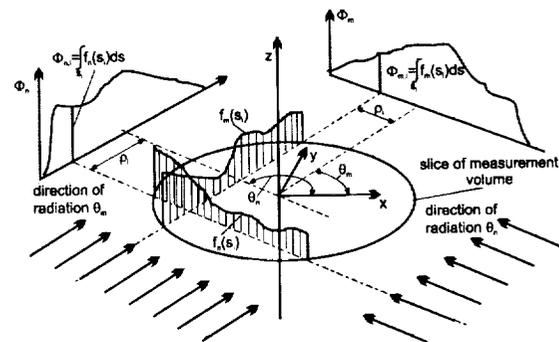


Figure 5. Principles of tomographic measurement techniques

shift is visualized through the interferometric fringe pattern and represents projection values. Mathematically, these projection values Φ_i are described as

$$\Phi_i(\rho_i, \theta_i) = \int_{s_i} f(x, y) ds. \quad (5)$$

Eq. (5) describes the projection value Φ_i , that corresponds to the average value of the field function $f(x, y)$ along the ray path s_i . If the field function f is kept constant along the ray path s_i , the value of the field function f and the value of the projection value Φ_i will be identical. This is the case in the study 2D temperature fields applying HI, which requires one direction of illumination only. Consequently, in order to extend HI to three dimensions, more directions of illumination are required, and tomographic reconstruction techniques are needed to recover the field function f from the measured projection values Φ_i .

A computer code for tomographic reconstruction of unsteady 3D temperature fields from 2D projections has been developed at the HTL in the first phase of this study. The ART (Algebraic Reconstruction Technique)-Sample Method (Lübbe, 1982, Ostendorf and Mewes, 1988) was selected for this heat transfer application based on previous positive experience with comparable physical situations. The Sample Method is based on a discrete Fourier transform, and as result an underdetermined system of equations is obtained. This system of equations can be solved in an iterative process with the ART-Algorithm.

The discrete Fourier transform is applied to the projection values Φ_i obtained for one direction of illumination. These projection values Φ_i correspond to a 1D function in the physical space, as shown in Figure 5. The result of the Fourier transform will be a 1D spectrum. The same procedure can be applied to another direction of illumination, and consequently, two spectra in the Fourier domain are obtained. These

two spectra are then connected in the Fourier domain under an angle corresponding to the angle $\Delta\theta = \theta_m - \theta_n$ between the two directions of illumination. The angle $\Delta\theta$ is also shown in Figure 5. The spectra of many directions of illumination form a 2D function in the Fourier domain. After applying the inverse 2D Fourier transform to this 2D function in the Fourier domain, the field function f is recovered. As a result of these mathematical transformations, the following system of equations is obtained

$$\Phi_i(\rho_i, \theta_i) = \sum_m \sum_n w(a_i, b_i) \cdot f(l_x m, l_y n). \quad (6)$$

The system of equations (6) has $m \times n$ unknowns corresponding to the number of grid points. In order to find a unique solution, $m \times n$ projection values Φ_i are necessary. In medical applications this requirement is satisfied by taking projection values using angle subdivisions of 1° . Apart from a sufficient number of projection values Φ_i , this method also ensures an accurate representation of the 2D function in the Fourier domain, since 180 spectra are available.

The Sample Method is a powerful tool to obtain a high spatial resolution in 3D tomographic measurements. However, to obtain high temporal resolution,

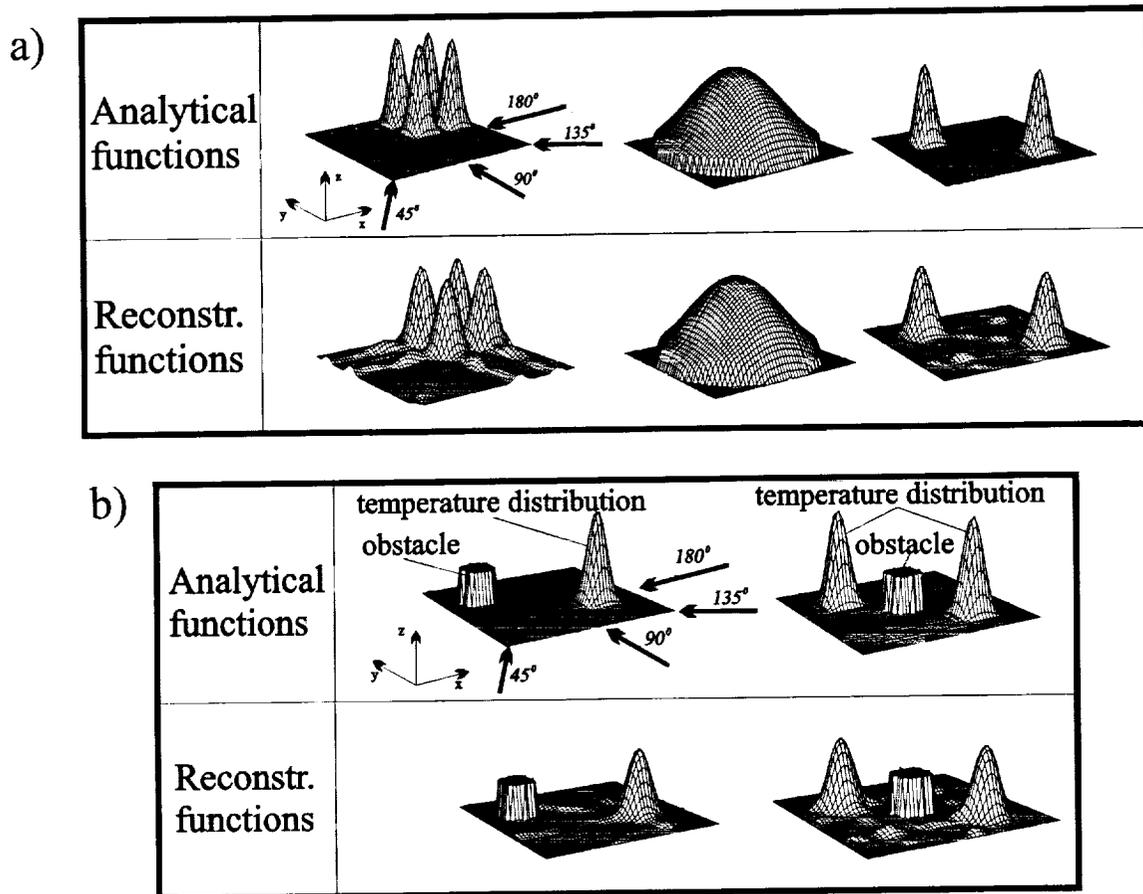


Figure 6. a) Three dimensional test functions and the corresponding reconstruction obtained by tomographic methods. b) Two analytical test functions with a cylindrical obstacle in the measurement volume and the corresponding reconstruction obtained using tomographic techniques.

In Eq. (6) l_x and l_y denote the size of one grid element, and m and n the coordinates of the grid points in the x and y directions, respectively. One should note the weight factor $w(a_i, b_i)$ that appears in Eq. (6). The weight factor is a function of the ray i , where a_i and b_i denote the slope and the intercept of the ray i . The form of the weight factor $w(a_i, b_i)$ was discussed by Mewes, Herman and Renz (1994).

as required in the present study, the number of projection values has to be decreased. This leaves the system of equations (6) underdetermined. The solution to this problem is the ART-Algorithm that iteratively determines the values of the field function f . In fact, the ART-Algorithm allows the reconstruction of the field function with 4 directions of illumination only, and 50 rays per direction for a grid size of 50x50 grid

points. Applying the Sample method alone would require 2500 projection values instead of 200.

The code developed at the HTL allows the reconstruction of the field function for different types of irradiation and different shapes (circular and rectangular cross section) of the measurement volume. The accuracy of reconstruction was evaluated by using analytical test functions, and the results of these tests are shown in Figure 6. The four directions of irradiation are also indicated for the first test function.

In order to apply HI to heat transfer measurements, both the investigated fluid and the vessel containing the fluid have to be transparent. Since the light beam is normally reflected at the liquid-vapor interface of the bubble, the bubble will act as an opaque obstacle in interferometric measurements. We have also applied our tomographic reconstruction algorithm to the reconstruction of the 3D field function to the situation when opaque obstacles are present in the measurement volume. The presence of an opaque obstacle prevents the probing light beams from traversing the measurement volume. As consequence, information on the average value of the field variable will be missing in regions that are in the shade of the obstacle. The reconstruction algorithm was modified to account for the presence of the obstacle and the analytical test functions used in this study as well as the corresponding tomographic reconstructions are shown in Figure 6b. Modification of illumination angles and beam numbers may be necessary to achieve the desired measurement accuracy in the study of boiling.

In order to obtain information necessary for tomographic measurements, the basic optical arrangement for in-line HI has to be modified to allow different transillumination directions. Fiber optics will be used to generate the four ray bundles needed for tomographic measurements instead of bench optics used by Ostendorf and Mewes (1988).

CONCLUDING REMARKS

Holographic interferometry was applied to visualize bubbles injected into the thermal boundary layer to simulate boiling. The initial experiments indicate that temperature distributions around the bubble are generally three dimensional. Two reconstruction algorithms, one assuming axially symmetrical temperature distributions and one for 3D temperature fields, were developed. Currently visualization experiments are being conducted in the heat transfer laboratory of the Johns Hopkins University.

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